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Towards a global model for wetlands ecosystem services☆

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Wetlands play an important role in the provision of important ecosystem services like the provision of clean water to the world, adaptation to climate change, and support for biodiversity; although they are sometimes also associated with adverse climate effects. Wetlands are, however, currently grossly underrepresented in global environmental models. In this paper, we explore the required functionality of a generic model of the effects of climate and land-use changes on wetlands ecosystem services worldwide. We briefly review existing models to identify elements which can be combined to compile a generic wetland model.

The proposed global wetland model should be integrated into and receive data from existing hydrology and climate models. Wetland delineation can be based on local hydrological and topographical conditions and verified with global wetland databases. We conclude that an integrated approach combining hydrology, biogeochemistry and vegetation for wetlands is not available yet, however, useful building blocks exist that can be combined.

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Introduction

The Sustainable Development Goals [1] require the sustainable use of the world's water and land resources to ensure food and water security, biodiversity and resilience to climate change. Wetlands are important for delivering these ecosystem services because of their regulating functions in the global water cycle, high productivity and biodiversity [2,3•,4] and their estimated value is proportionally much higher than their current modest 5–6% share of global land-use [5]. Forested watersheds and wetlands supply three-quarters of the world's freshwater for humans and nature [6]. Conversion of these natural lands into farmland during the last century has increased global annual river discharge by about 5%, according to a global model study [7]. Wetlands generally increase resilience to climate change by buffering against droughts and floods (although with exceptions) [8], storing carbon and, if untouched, cooling the climate in the long-term [9•,10]). On the other hand, wetlands may be associated with processes that are adverse to human well-being ('disservices') like methane emissions and water-borne diseases [9•,3•]. In the past decade, an ecosystem approach to land and water management has been advocated, for instance by utilizing more 'green water' for agriculture and reducing the pressure on 'blue water' resources [11,7,6].

Despite their ecological and economic values, about two-thirds of the world's natural wetlands have disappeared since 1900, based on existing data [12]. This loss is continuing, mostly for agricultural and urban

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development [13,14]. Remaining wetlands are threatened by hydrological change and nutrient enrichment, driven by population growth, economic development and climate change [15,3•].

Policymakers recognize the importance of healthy wetlands for achieving the SDGs and are concerned about their loss. At the global level, this has been emphasized by the conventions concerned with sustainability (Ramsar, UNFCCC, UNCCD and UNCBD), and by UN organizations such as FAO and UN-Water. The Ramsar Convention list of wetlands of international importance covers 13–18% of the world's wetlands [16•] but not all 170 signatory countries are successful in implementing the convention [17]. This raises strategic questions about the current Ramsar sites: if well-managed, would they be sufficient for providing critical ecosystem services worldwide? Does the current list include the most crucial wetland areas for resilience to climate change? And how should 'sustainable use' be defined (e.g. [18])?

Global earth surface models, dynamic vegetation models and integrated assessment models have contributed significantly to policy making by evaluating the impact of land use change on climate, food security and biodiversity [19•,20,21]. However, wetlands and their ecosystem services are mostly neglected in the current global models. When included, the focus is on disservices like potential methane emissions of wetlands [22] or on their beneficial carbon sequestration function [23]. Although several modelling studies of specific wetland types or regions have been helpful for land-use planning or management, a global framework that integrates hydrological, biogeochemical and vegetation processes of wetlands is currently lacking. The need for a global framework has been inspired by the increasing global problems of climate change and land use, while recognizing that the existing regional wetland models do not provide adequate global coverage. The model should however acknowledge the great diversity that exists between wetland types. This paper is a plea to develop such a model, in order to explore the contributions of wetlands to solving global food and water problems more effectively. The model could be used for periodic assessments of wetland extent, it could help prioritize wetlands for protection and would evaluate synergies and trade-offs in ecosystem services (e.g. water provision) and disservices (e.g. GHG emissions) resulting from alternative policies or management scenarios. Prospective users of the model are policy and decision makers from international conventions and organizations, regional and national governments, NGOs and the private sector.

The overall goal of this paper is to explore the outlines of a generic, process-based global wetland model that can be used to evaluate the effects of climate and land-use change on the areal extent and key ecosystem services of wetlands worldwide and to assess synergies and trade-offs. First, we delineate the model based on the required functionality. Then we review existing wetland models, and finally propose the elements needed for a global wetland model.

Functionality and delineation of a global wetland model

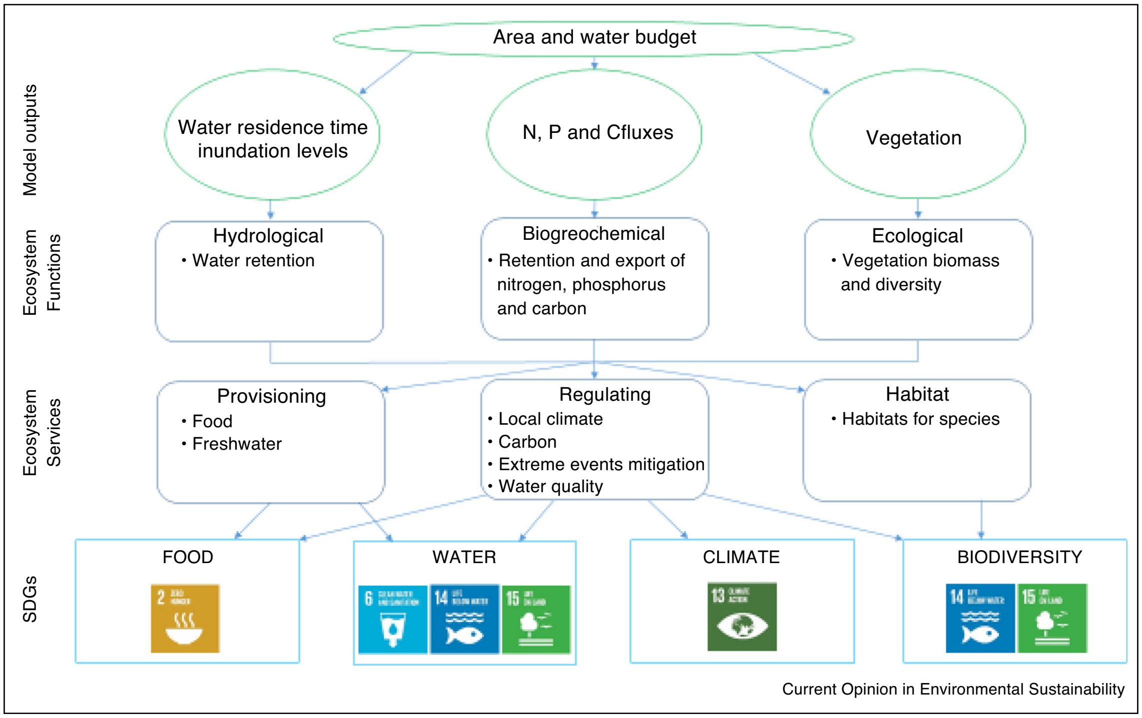
Definition of wetlands covered by the model

At this stage, we confine ourselves to inland wetlands; coastal wetlands are excluded. Wetlands are defined as permanent or seasonal (inundation occurring every year) water bodies dominated by emergent vegetation and/or areas with a permanently water-logged soil. We consider only natural wetlands, which may however be used seasonally for agriculture or livestock grazing. Artificial wetlands, used for permanent agriculture (like rice-fields) or water treatment are not included. We also exclude stratified lakes, as we focus on ecosystems dominated by emergent vegetation, noting that the boundary with shallow lakes is not fixed. We strive for coherence and possibly linking with global-scale modelling efforts for lakes [24]. Our definition comprises more or less the water types 4, 5, 8 and 10 and a part of type 1 of the Global Lakes and Wetland Database [25]: floodplain wetlands, swamp forests and mineral marshes, peatlands (bogs and fens) and shallow lakes, together now covering about 5–6% of the world's continental surface. While this classification is mainly GIS-based, for modelling it needs to be linked to hydrological, hydrogeomorphic and chemical features. Major criteria for wetland classification are the proportion of atmospheric, groundwater and surface water as water source, the water renewal time and landscape type (upland, slope, valley, depressions, flat lowland) [26•]. It seems appropriate for the global model to use a classification based on these criteria. Based on increasing water renewal rate, some major classes will be defined within the continuum from peatlands (bogs and fens) to river floodplain wetlands, which may be further subdivided if needed.

Required functionality: ecosystem functions and services

The global wetland model should allow the quantification of ecosystem services in relation to environmental change and anthropogenic pressure [27]. Five elements of wetlands, that is areal extent, water budget, water level fluctuation (i.e. intermittent or permanently inundated fractions), nutrient fluxes, and vegetation, determine the hydrology, biogeochemistry and ecosystem characteristics or ecosystem functions [28] underpinning the ecosystem services specified in Figure 1 that contribute to achieving the SDGs [29]. This set-up will allow evaluation of the influence of pressures such as land use change, pollution and climate change on wetland size and ecosystem services and disservices. By linking the ecosystem services to the corresponding

Figure 1



Relation between model outputs, ecosystem functions and services and SDGs.

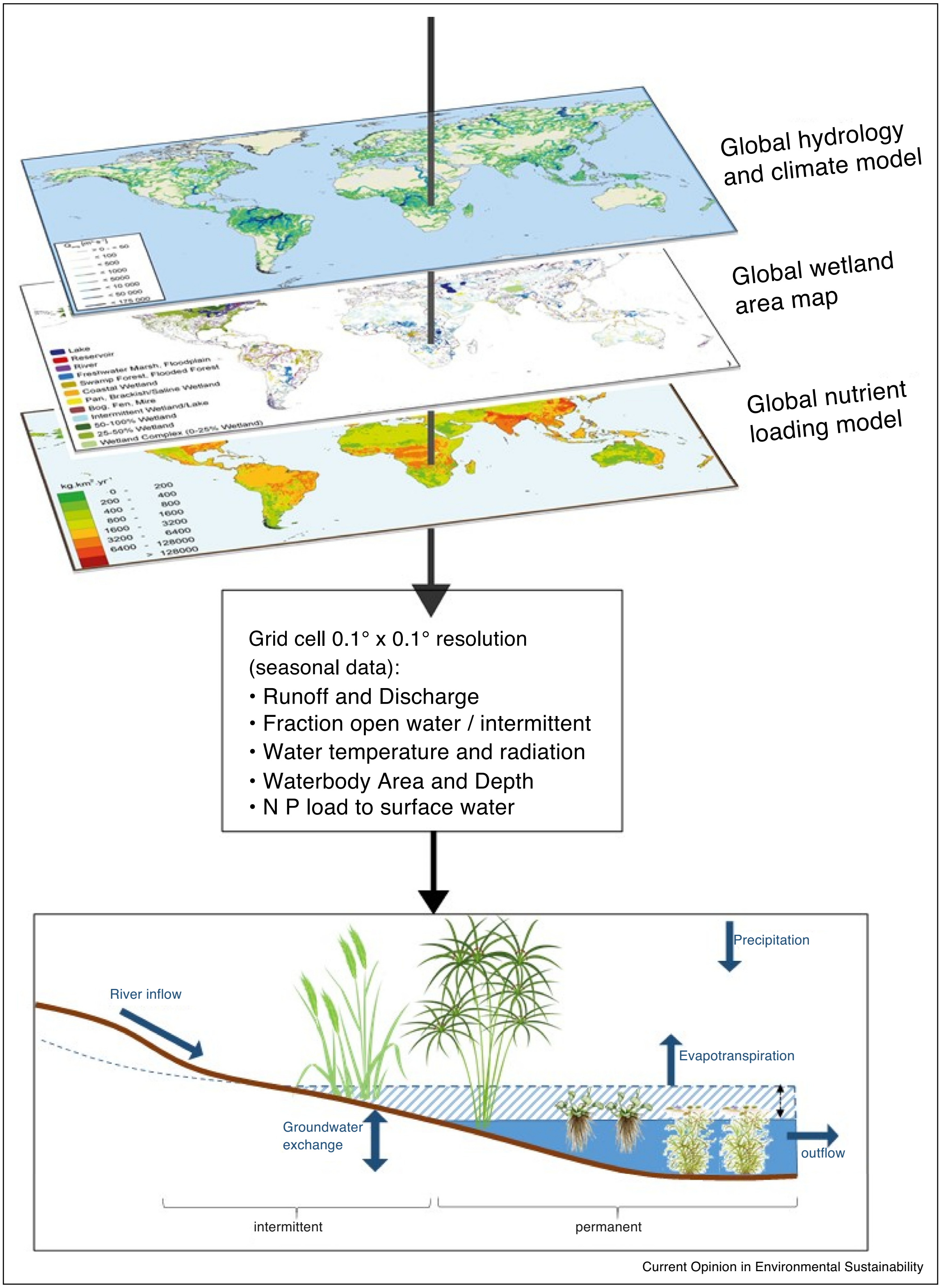
SDG indicators, the model will also show the impact of these pressures on human well-being. Biodiversity indicators can be linked to these elements, either directly or through empirical 'add-on' models (e.g. [30]). Other wetland benefits that are related to wetland area and functioning, such as recreation and contribution to pollination and biological pest control can be expressed in semi-quantitative terms.

Table 1

Main input and output variables of the proposed process-based model

A. INPUT from other models or databases			
Component	**Parameter**	**Unit**	**Data sources**
Wetland map	Area, location and type	km^2	GLWD and other maps
Water	Water inflow	m^3 month^{-1}	From global climate and hydrological model
Climate	Rainfall, evapotranspiration, temperature	m^3 month^{-1}; m^3 month^{-1}; °C	From global climate model
Land-use and nutrients	N and P input	kg yr^{-1}	From global land-use and nutrient model
Soil and slope			FAO soil map; DEM
B. OUTPUT variables			
Component	**Parameter**	**Unit**	**Relevance for ecosystem services**
Wetland area	Change in wetland area and distribution	km^2	All services
Water	Volume	km^3	Water availability; biodiversity
	Inundation and water level fluctuation	m yr^{-1}	Retention and vegetation; biodiversity
	Water retention time	For example month	Water availability; flood protection; climate change adaptation
N and P	N and P retention	fraction of yearly input	Retention function
Carbon	C sequestration	kgC km^2 yr^{-1}	Climate change mitigation
	C emissions, incl. CH4	kgC km^2 yr^{-1}	Greenhouse gas emissions
Marsh vegetation	Production	kgC km^2 yr^{-1}	Retention; production; biodiversity
Floating vegetation	Production	kgC km^2 yr^{-1}	Retention; production; biodiversity
Submerged vegetation	Production	kgC km^2 yr^{-1}	Retention; production; biodiversity

Figure 2



Proposed model set-up: key elements and main input data: hydrology & climate, geography & typology, and land-use.

Key elements

To achieve the objectives outlined above, a global model needs to comprise at least the following functional components, in a dynamic way: area, volume (water depth), water retention time, nutrient pools (N, P, C) and retention in water and soil, and emergent and floating vegetation (Table 1 and Figure 2). On the input side, the wetland model should be easily linked with (spatially explicit, in order to cover regional differences) land-use, climate and hydrological data.

The model needs to produce quantitative estimates of a number of ecosystem services on the basis of the prevailing environmental conditions and wetland ecosystem functioning. Environmental conditions are defined by ambient temperature regime, water level, water chemistry and nutrient conditions. The functioning of the wetland system is determined by the interaction between these environmental conditions and the dominant wetland vegetation.

Global-scale input: hydrology, climate and land-use

On the input side, the wetland model should be easily linked with (spatially explicit) land-use, climate and hydrological models, data and maps as used in other parts of the model chain (Table 1 and Figure 2).

The hydrological basis for the model consists of a global hydrological model which can calculate a water balance for every areal unit (e.g. a grid cell) on the basis of a digital elevation model, land-use and climate data such as rainfall, snowmelt and evapotranspiration, which are derived from global climate models. A number of hydrological models exist [31,32], such as PCR-GLOBWB [33], WaterGap3 [34], WBM [35], LPJmL [7] and VIC [36]. All of these are grid-based models, at scales varying between 5 arc min and 1°; PCR-GLOBWB also includes an inundation module for river floodplains. Currently some of these models are being downscaled or linked to a more detailed river network map [31], while another study tried to develop a dynamic wetlands extent scheme as an 'add-on' to global hydrological models [37]. A grid-based model at a 5 arc min scale ($\sim 9 \times 9$ km at the equator), including a downscaling procedure within floodplains (to account for inundation flow of floodplain wetlands by adjacent rivers), seems to be the minimum required for global wetland modelling. The model should also include water abstractions for agriculture and domestic and industrial use, which lead to changes in discharge and water availability for wetlands. Furthermore, a dam operation module for at least the larger reservoirs is required, as dams can substantially decrease the water flow to floodplain wetlands [38].

As a second input, projections are needed on important drivers of change, such as drainage and conversion of wetlands into agricultural land, and the releases of nutrients into surface water from agricultural and urban sources. These factors can be derived from a global land-use and nutrient model, such as the model MARINA [39] or GNM [40•], which is embedded in the integrated assessment model framework IMAGE [41] as a link with population growth and socioeconomic development.

Water budgets

Based on the runoff conditions predicted by the hydrological model, the prerequisites for the existence of wetlands: permanently or seasonally inundated areas, can be determined. In this way, the model can, in principle, predict both the extent, the volume and water level variation of the main types of inland wetlands (from peatlands to floodplain wetlands; see Section Definition of wetlands covered by the model) and their principal sources of water: precipitation, groundwater and flowing surface water. Predictions need to be validated on existing GIS-based and RS-based surveys [16•,42].

As water levels in wetlands typically show seasonal variation, parts of the wetlands alternate between periods of inundation and draw-down. This has important consequences for their ecological functioning and use and has to be accounted for in the proposed model (Figure 2). Pragmatically, we suggest distinguishing a permanent and an intermittent zone, the proportions of which may vary in time. As for the temporal scale, a scale of months seems appropriate to grasp the main seasonal differences.

Nutrients, carbon and vegetation

The basis of the model will be dynamic, allowing for prediction of non-linear system responses to changes in drivers. The model will include process descriptions for carbon, nitrogen and phosphorus, and a generic module for a few dominant wetland vegetation types, using basic process descriptions and additional empirical relationships. Vegetation type will be determined based on a limited number of wetland vegetation types (emergent, floating, submerged) and species known to be dominant for the ecoregion. Periphyton will be included as an important factor that can suppress vegetation, and possibly phytoplankton (although it is mostly not abundant under emergent vegetation). The vegetation module can be parameterized to predict aboveground and belowground biomass and nutrient uptake and release for locations that differ in hydrochemical and climatic conditions. The model will calculate a mass balance of carbon and nutrients based on photosynthesis, assimilation, nutrient uptake and mortality of the vegetation, and the cycling of organic and inorganic matter, and carbon uptake and emissions.

Review of existing models

Review set-up

To identify any existing models that could serve as prototypes for a global wetland model or provide useful

Table 2

Processes and components of selected 'prototype' wetland models

		Wetland-DNDC	Papyrus Simulator	Phragmites and Typha models	PCLake marsh module	Peatland-VU	PEATBOG	Phragmites C model
		Zhang [43]	Hes [44]	Asaeda [45]	Sollie [47], Janse [46]	Van Huissteden [48]	Wu and Blodau [49]	Soetaert [50]
Hydrology	Surface water	+	+	–	+	–	–	–
	Ground water	?	–/+	–	–	+/–	+	–
Carbon processes	Open water, sediment	+	–/+	+	+	–	–	+
	Soil	+	–/+	+	–	+	+	+
GHG emissions		+	+/–	+	–	+	+	–
Nitrogen processes	Open water, sediment	+	+	+	+	–	–	–
	Soil	+	+	+	–	–	+	–
Phosphorus processes	Open water, sediment	–	+	–	+	–	–	–
	Soil	–	+	–	–	–	–	–
Vegetation		Various	Papyrus	Phragmites; Typha	Phragmites	Peatland	Various	Phragmites
Trophic links		–	–	–	+	–	–	–
Management		–	+	–	+	–		+
Climatic region		Various	(Sub)tropical	(Sub)tropical	Temperate	Temperate	Temperate-boreal	Temperate

Symbols: + included, +/– partially included, –/+ limited included, – not included.

building blocks, we performed a literature survey using Scopus and Google Scholar using the keywords 'wetland', 'model', 'hydrological' and either 'biogeochemical' or 'vegetation'. From the resulting references, purely hydrological wetland models were not further considered as for the purpose of the global wetland model a global hydrological model is required as input. The remaining models, viz. Biogeochemical and nutrient models (20 papers) and Vegetation models (27 papers), are listed in the Appendix in the Supplementary material. The models were screened for the following aspects: model type, wetland type, input variables, output variables, scale, and usefulness for our purpose.

Review results

The survey revealed a wide variety of model approaches, from dynamic simulation models to purely empirical models. Every model focuses on specific aspects. Many models are designed for specific wetland types or regions or have an otherwise restricted scope. Often, models were validated against an (independent) set of field data, but few were applied outside their developing domain.

No single model covered all elements needed to describe the desired regulating functions (see Section Functionality and delineation of a global wetland model). Nevertheless, a combination of elements from a few existing models seems to offer a suitable basis for the vegetation and nutrient process model, which can then be improved and completed based on other sources. As 'prototype' models we chose process-based, dynamic models that include emergent vegetation growth and at least one nutrient, have generic properties rather than being restricted to specific circumstances, and preferably include a notion of permanent versus seasonal inundation. The following models, listed in Table 2, satisfied these criteria: DNDC [43], the Papyrus Simulator [44], the Phragmites and Typha models by Asaeda [45] and the PCLake-marsh module [46,47], together with the models Peatland-VU [48] and PEATBOG [49], both for peatlands, and the Phragmites C model by Soetaert [50].

Conclusions

We explored the outlines of a global wetland model in view of the required functionality. We conclude that the elements area, water budget, inundated fraction, nutrient fluxes and vegetation are key factors for the processes that determine the main ecosystem functions and services. We consider it in principle feasible to build such a global model, based on existing generic knowledge on wetland processes, and the availability of hydrological and land-use models to provide important inputs.

Second, we observe that an impressive set of wetland models have been published and applied in case studies, but currently no model exists which combines all key elements on a global scale. An integrated approach combining hydrology, biogeochemistry and vegetation for wetlands is not available yet, however useful 'building blocks' exist. Combining these from a selected set of 'prototype models' seems a feasible and efficient way to compile such a generic model. Further elaboration and parametrization can be done using additional information from other models that are more restricted in scope and

from GIS and remotely-sensed data [51,52]. This approach will allow the model to be as generic as possible but contain sufficient detail to grasp broad differences between regions or wetland classes.

Being a feasible effort, a number of challenges will have to be dealt with. A main issue is to acknowledge the large regional differences between wetland types while keeping the global picture in sight. This variation is probably one of the reasons that a global wetland model is currently lacking. First, there is the issue of wetland typology. While the major criteria for global wetland classification have been defined [26•], further subdivision of wetland classes may be needed to capture regional differences in their functioning. This can be based on a set of HydroGeoMorphic Units (land units with homogeneous hydrology, geomorphology and soils), which is so far mostly done at the landscape scale. It will be necessary to define a limited number of broader HGMUs that would be suitable as subclasses to be used in the global modelling exercise. Another question is whether the resolution of the hydrological model(s) will be adequate to provide the required input at the desired scale. By choosing a close link with a global hydrological model and spatially explicit land and soil data, the proposed model may in fact be regarded as an aggregate of (larger) catchment models. Third, it will be a challenge to select an adequate set of parameters to define the broad vegetation classes. We propose to derive these from an empirical approach when possible rather than from a full competition model, and then link them with the dynamical process formulations. And finally, a strategy will be needed to deal with uncertainty, not to get discouraged by it but to interpret the variability in view of the purpose of the global model that is providing a global picture of wetland ecosystem services.

The proposed generic model could well be used to better quantify the important—and often unrecognized—role of wetlands for climate change mitigation and adaptation, water storage, nutrient retention and other services, and define feasible scenarios for the maintenance and restoration of these important ecosystem services wetlands provide to humanity and to minimize the 'disservices' It could contribute to mores and better 'Tier 3' estimates of greenhouse gas emissions and carbon storage in wetlands, taking into account climate variability, land use change and interannual variability [53].

Conflicts of interest statement

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cosust.2018.09.002.

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